Heavy ion fusion (HIF) driver point designs ☆

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Abstract

In this paper we report on two Heavy Ion Fusion (HIF) driver point design studies. The Robust Point Design (RPD) was completed over a year ago, and the Modular Point Design (MPD) is still in progress. The goal of any point design study is to construct a detailed design that is self-consistent and integrated from injector to target. This has been the primary theme of both studies.
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1. The Robust Point Design

The Robust Point Design (RPD) [1] is based on the multi-quadrupole-focused induction linac approach to the Heavy Ion Fusion (HIF) driver. The economic and technological advantages of this

approach have been discussed in many previous conferences. The scaling is such that many beams are actually favored. The limit to the number of beams is set by how closely we can pack adjacent beams, which is in turn determined by the technology of multi-quad arrays, and the physics of the fill factor. The fill factor issue has major implications for driver economics and is addressed by the High Current Experiment (HCX) program [2]. In this approach, the beams in the multi-quad array are accelerated within one large induction core. Each beam, however, has its own injector. Hence, compact injectors are essential for the economic viability of this concept. The merging beam program of the VNL [3] is designed to address this specific issue.

The major new efforts of the RPD study center around the region in the proximity of the target chamber. The reason for this emphasis is that there are many components with differing requirements in this region, and until a point design is constructed, the technical viability of a self-consistent driver solution is not given. More specifically, we have the target, the chamber, final beam transport, final focus magnets with their large bore and shielding requirements, and the chamber/final magnet interface. All components must be self-consistent and compatible with the upstream drift compression sections, the accelerator, and the injector architecture.

The target symmetry and pulse shape requirements lead immediately to a minimum number of beams in the RPD. The pulse shape required of the target has a foot pulse and a main pulse with specified temporal dependence. If we try to construct a single beam with this pulse shape, the longitudinal self-fields will blow the beam apart during its passage through the drift compression and final focus regions of the driver. The approach we took was to construct the final pulse shape out of five building blocks, each of which had a flat top that was compatible with drift compression and final focus. In addition, symmetry requires at least eight beams from each side, or 16 beams for each block for a two-sided target. The beams were furthermore checked for acceptable current (perveance) for transport through drift compression and final focus. This results in a

minimum of 120 beams (the number adopted for the RPD).

The distributed radiator target for the RPD had to be modified to accept a wide angle of 24° for the entire 120-beam array. This was possible with a penalty of 1 MJ to a total required energy of 7 MJ.

The main reason for adopting 120 beams, and not some higher multiple came from the chamber with the stationery Flibe jet array for beam entry. The geometry of nozzles and jet formation limits us to a maximum of 11×11-crossed jets. Sixty beams per side is compatible with a 9×9 array, which presents a much more optimal Flibe jet pattern than the maximum 11×11. The combination of oscillating and stationary jets provide 4π protection to the chamber walls except for the "holes" required for beam and target injection.

The chamber [4] is slightly less than 3 m in radius, but the last final focus quadrupole is 6 m away. In the 3 m between the last quadrupole and the chamber wall, we have pipes that are lined with Flibe vortices and a weak ($\sim$kG) short dipole magnet, which acts as a debris shutter. There are two short sections at 3 m and 6 m respectively for plasma injection to provide a "plasma plug" for neutralized final beam transport through the chamber. This 3 m drift section has the four-fold function of magnet protection, differential pumping with the Flibe vortices acting as an effective getter (from 10^{-3} to 10^{-6} Torr), debris blocker and plasma plug.

Neutralized drift of the heavy ion beam through the last 6 m to the target has been the subject of intense simulation efforts in the previous two years. With all known physics of plasma plug, beam ionization, photo-ionization, and beam stripping incorporated into the 3-D PIC code LSP [5] it has been demonstrated [6] that both the foot pulse and the main pulse can be delivered to the required 2 mm radius spots on target.

Our choice for the beam was Bismuth $+1$ entering the fusion chamber drift section at 10 m convergence half-angle. The choices of ion mass as well as convergence angle have large impacts on the upstream accelerator and final focus magnet design. The choice of a heavy ion minimizes the perveance, which in turn makes beam transport easier, at the expense of a longer and more

expensive accelerator. We made this initial choice to enhance our chances of a self-consistent solution when all components are integrated. From the perspective of neutralized drift alone, we could have gone to a lower mass ion (like Xe) and/or smaller convergence angle, based on simulations completed after the RPD studies.

The final focus beam transport was designed with a combination of envelope codes and WARP 3D [7]. We adopted a four-quad final focus magnetic system. The geometric aberrations from this system were shown to be acceptable (no large emittance growth) [8].

While the quadrupole fields and gradients were not very high, yet because of the large quadrupole aperture, these superconducting magnets turn out to be nontrivial to design and build. Final design was arrived at with some reasonable extrapolation of present-day magnet technology.

A mechanical design of the 60-beam array was constructed, incorporating into the inter-quad spacings enough shielding material to assure lifetime of components against radiation. Issues of assembly and maintenance were folded into the mechanical designs.

Finally, 3-D neutron and radiation transport calculations were performed [9], and the final design had a lifetime of the order of 100 years for all magnets, exceeding the required plant lifetime of 30 years. The Waste Disposal Rating of the magnets was determined to be Class C waste. Again, these final results of the shielding calculations indicate that we had some margin in our design, and room for further optimization with the next iteration.

The accelerator required for this driver was designed using the system code IBEAM [10]. This accelerator, not unexpectedly, was relatively long (3 km) and the cost of the driver was close to $3 billion.

We should note that the drift compression section was not designed in detail. These 120 beam lines would have to have slightly different path lengths in order to achieve the proper timing at target. We do not believe that this is a feasibility issue, but could add to the complexity of the final design.

This multi-disciplinary effort has led, in our opinion, to a credible self-consistent design.

However, it is also clear that the final product was far from the economic optimum. There is still plenty of room for further optimizations.

2. The Modular Point Design

The Modular Point Design study (MPD) is an ongoing activity. The basic concept is an HIF driver with some tens ($\sim$10–40) of modular induction linacs, each carrying a single beam with high line charge density, and are by and large independent until they reach the target chamber. The primary motivation of this approach is the relatively straightforward development path from a small-or medium-scale Integrated Beam Experiment (IBX) to an Integrated Research Experiment (IRE), which will be one module of the full fusion driver. However, this approach also implies new technological and beam dynamics challenges, many of which have been described elsewhere in these proceedings.

Central to this approach is the physics of Neutralized Drift Compression (NDC) [11]. The basic concept is to impose a velocity tilt on the beam with high-energy particles at the beam tail, and low-energy particles at the beam head. This beam is injected into a long drift section filled with plasma. Longitudinal space charge that acts to oppose compression is nearly eliminated. It is this new scheme that allows us to access the high perveance regime required for the few-beams approach. LSP simulations have been performed and are continuing in earnest, and small-scaled experiments (the NDCX series) have been planned.

The favored intra-accelerator transport scheme, particularly in the low-energy end, uses solenoids. At the high-energy end, options for solenoids as well as quads exist. The primary reason is that the line charge density confined by solenoids depends quadratically on the magnetic field strength and beam size, and is independent of the beam energy. Furthermore, the line charge density is linearly proportional to q/M of the ionic species. Hence it favors the lower mass ions, which in turn implies a short accelerator with reduced cost per accelerator. The cost tradeoff, in comparison to the

conventional multi-quad approach, has to do with many short, and smaller diameter linacs versus one somewhat longer and larger diameter linac. The economic issues are addressed elsewhere in these conference proceedings [12].

This scheme also requires a high line density injector. Several options are being considered. The accel/decel injector with load and fire is being studied in some detail, and there are also plans for a near-term experiment [13].

As in the RPD, the main efforts in MPD lie in constructing a self-consistent design in the target chamber end of the driver.

The target we have adopted for the MPD is the hybrid target described by Callahan et al. [14]. Like the Distributed Radiator target of the RPD, it has symmetry and pulse shape requirements. It has the major advantage of a larger spot size (∼5 mm radius). However, the design is such that the beams must come in at shallow angles ($<6°$). A $24°$ array, as in the RPD, would not match the hybrid target requirements.

One requirement imposed by NDC is that the beams will arrive at the target with a velocity tilt. This is in contrast to the conventional vacuum drift compression where the initially imposed velocity tilt for pulse compression is removed by opposing longitudinal space-charge forces towards the end of the drift compression. This is the so-called stagnation point. In the NDC scheme, the beams see no space-charge forces. Hence, whatever initial velocity is imposed will remain at target. Target designers are addressing the issue of velocity tilt at target. The higher the velocity tilt the target can accommodate, the shorter the length of the NDC section.

Since there are no space-charge forces, the final pulse shape can indeed be tailored by creating the appropriate velocity tilt waveform at the entrance to the NDC. This removes the constraints to a large number of beams, as in RPD, and in principle provides a pathway to compatibility between a few beam driver and target requirements.

The final focus scheme and the chamber concept must be compatible with the NDC immediately upstream and the target. Here, we have been working in parallel with two concepts. The first concept involves a new "vortex chamber" [15]. The idea is to protect the chamber with a thick layer of rotating Flibe. This is a new concept, and is in the early stages of development. However, it is based on the experimental work on vortices conducted at University of California at Berkeley over the past few years. It offers the possibility of nearly 4π protection (except for beam entrance ports on the two sides), and yet reduces the risks of multiple jet nozzles. External to the vortex chamber are large solenoids with relatively low fields of 1–2 T. The multiple beams leave their individual solenoid channels and merge immediately upstream of the entrance port to the vortex chamber. The final focus solenoids can be room temperature magnets which are much more resilient to radiation from the target blasts. The key question being addressed is the sensitivity to velocity tilt. Design work is ongoing to reduce the sensitivity of the beam optics to energy variations, and/or to correct with fast time-dependent magnets.

The second option uses two (opposing) current carrying channels from opposite sides of the two-sided hybrid target inside a slightly modified HYLIFE II chamber. This scheme is known as the "Assisted Pinch" and has been studied over the past ten years [16,17]. It is a natural match to NDC and the hybrid target requirement. This focusing scheme is very insensitive to energy spread and/or velocity tilt. The angle at which beam particles impinge on the target comes primarily with the betatron motion in the channel, and is less than $6°$ for typical channel parameters (∼50 kA). Finally, these channels have strongly nonlinear, focusing forces since the plasma current distribution is typically nonlinear. This leads to a strong phase mixing for the ion beam, thus completely symmetrizing the beam distribution at target, even if the beam enters the channel at an angle. This effect has been shown repeatedly in many simulations [18].

For an example of an integrated calculation from the exit of a solenoid accelerator, transitioning into a 100 m long plasma, and subsequent beam entry into an adiabatic plasma lens, and a final Z pinch. We cite the work of Welch et al. [11] reported also in this conference. This integrated simulation delivers 92% the total beam energy onto a target.

Table 1
Comparison of RPD and MPD to demonstrate the difference in approach

Driver components	RPD (M beams $M = 120$)	MPD (N modules $N = 10-20$)
Accelerator/Pulse Power System (PPS)	1 accelerator/1PPS	N accelerators/1PPS
Ion Species	Heavy-Bi (Xe possible)	Medium (Ne to Ar)
Injector	M compact injectors	N high λ injectors
Transport	Multiple quad array for M beams	Solenoid/hybrid (1 solenoid/module)
Drift compression	M vacuum drift compression beamlines	1 neutralized drift compression beamline/module
Final focus/chamber transport	Quad focusing/neutralized ballistic transport	Solenoid in plasma or assisted pinch
Chamber	HYLIFE II	Vortex chamber or modified HYLIFE
Target	Distributed radiator target with large angle	Hybrid target

3. RPD and MPD comparisons

The RPD and MPD are based on very different architectures. The RPD is based on the multi-beam, multi-quad approach, while the MPD is based on the premise of a few beams with high line density (see Table 1). While some of the components are interchangeable, the objective of each design is to construct a self-consistent, integrated concept from injector to target. The RPD is a completed piece of work, although much more progress in optimization could be made in the future. The MPD is work in progress, which we hope to complete in the coming year.

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